PERFORMANCE ADAPTIVE AEROELASTIC WING KICKOFF

OUR TEAM

- University of Minnesota
- Systems Technology Inc.
- Virginia Polytechnic Institute and State University
- Aurora Flight Sciences
- CM Soft Inc.
- Schmidt and Associates

AGENDA

- Purpose
- Motivation
- Objectives
- Overview
- Technical Approach
- Facilities
- Management Plan
- Schedule
- Areas for Collaboration
- Discussion

NASA Subsonic Transport System Level Metrics

…. technology for dramatically improving noise, emissions, & performance

TECHNOLOGY BENEFITS*	TECHNOLOGY GENERATIONS (Technology Readiness Level = 4-6)		
	N+1 (2015)	N+2 (2020**)	N+3 (2025)
Noise (cum margin rel. to Stage 4)	-32 dB	-42 dB	-71 dB
LTO NOx Emissions (rel. to CAEP 6)	-60%	-75%	-80%
Cruise NOx Emissions (rel. to 2005 best in class)	-55%	-70%	-80%
Aircraft Fuel/Energy Consumption‡ (rel. to 2005 best in class)	-33%	-50%	-60%

* Projected benefits once technologies are matured and implemented by industry. Benefits vary by vehicle size and mission. N+1 and N+3 values are referenced to a 737-800 with CFM56-7B engines, N+2 values are referenced to a 777-200 with GE90 engines

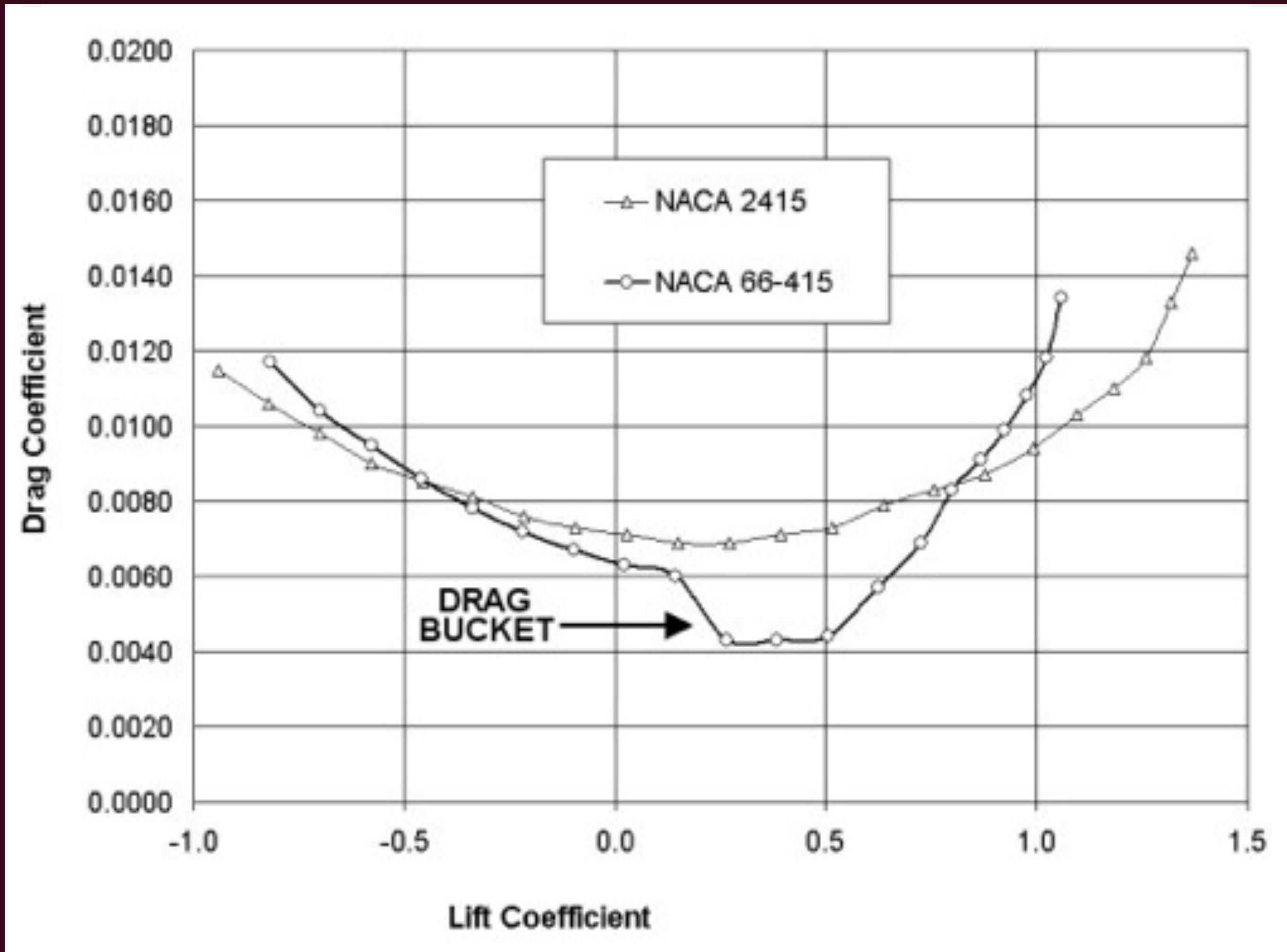
** ERA's time-phased approach includes advancing "long-pole" technologies to TRL 6 by 2015

‡ CO_2 emission benefits dependent on life-cycle CO_{2e} per MJ for fuel and/or energy source used

MOTIVATION

- Commercial aircraft are designed for a single operating point
  - Off condition weight, altitude, and speed decrease efficiency
  - Compromise between cruise speed and meeting landing requirements
  - Poor low speed characteristics require use of many flaps and slats

➡ High fuel burn and noise



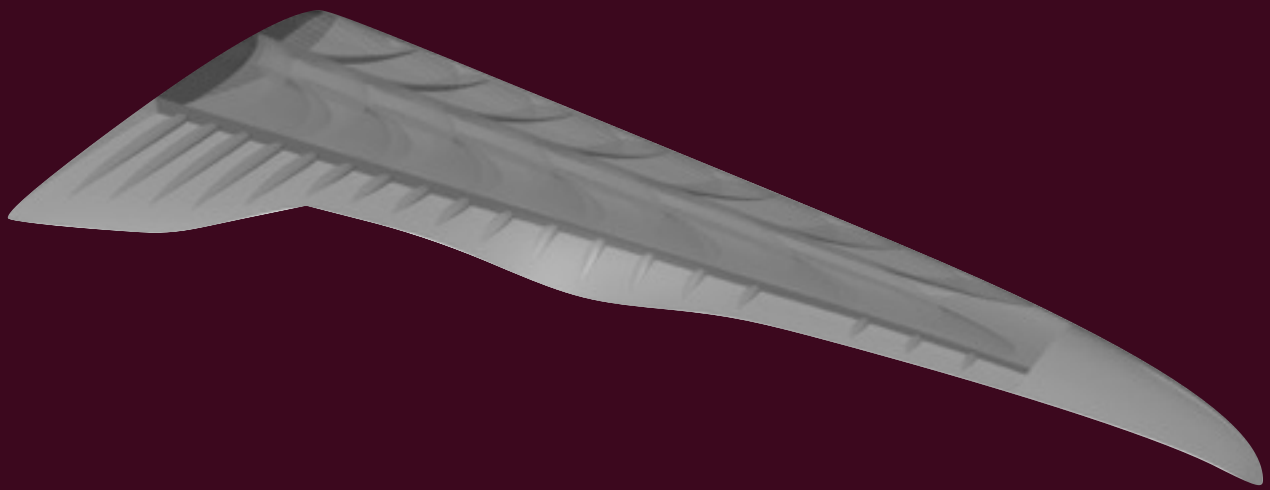
MOTIVATION

- Long, high aspect ratio wings are more aerodynamically efficient, but pose potential stiffness problems
  - Traditional aircraft design approaches favor stiff wings
  - High stiffness would lead to increased weight, negatively impacting fuel burn

➡ Expand the aircraft design space to take advantage of wing flexibility

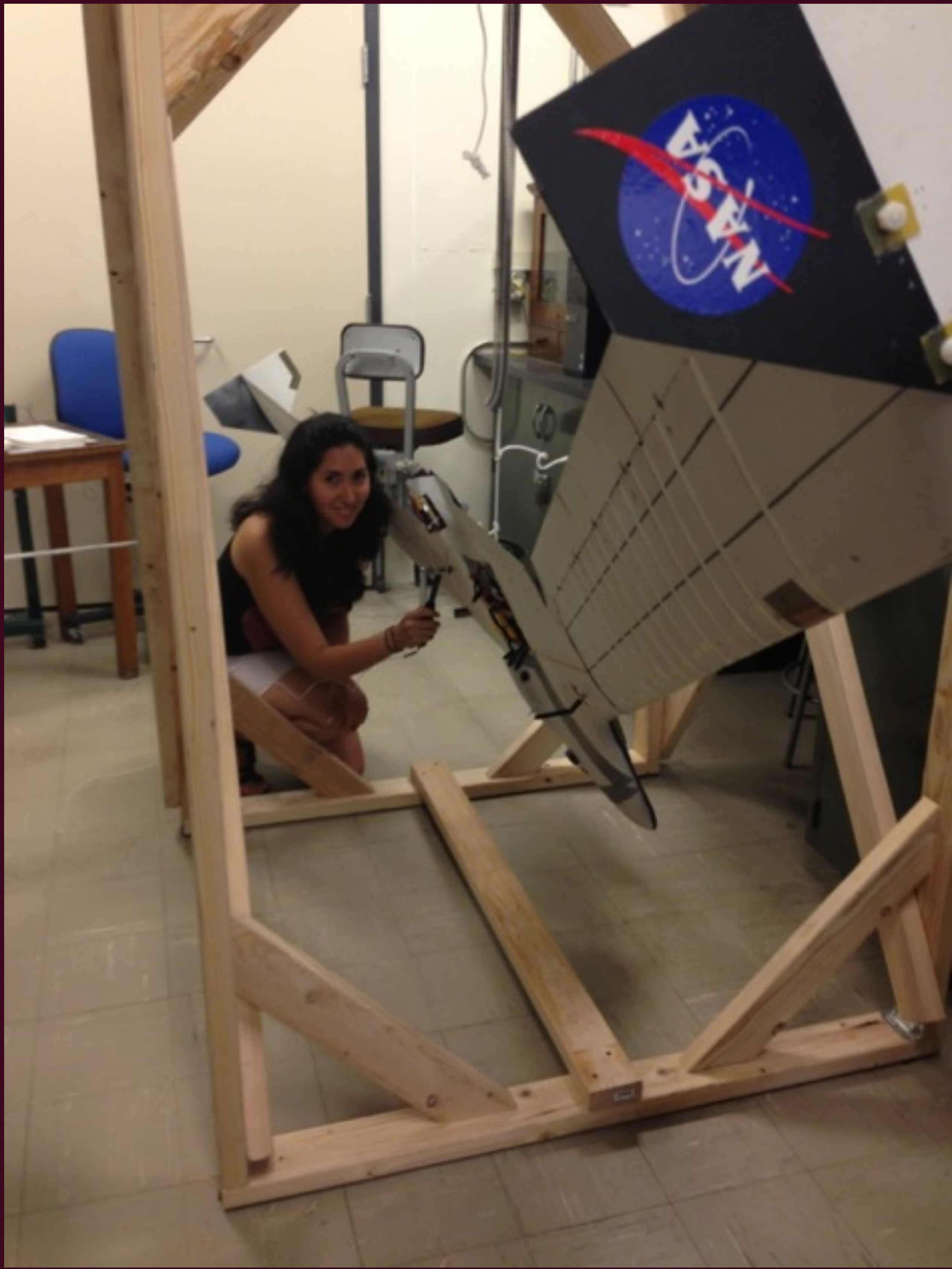
OBJECTIVE

- Research and develop performance adaptive wing for N+3 aircraft
  - Adapt wing to flight condition:
    - Minimize fuel burn in cruise
    - Maximize lift for takeoff
    - Maximize lift and drag for landing



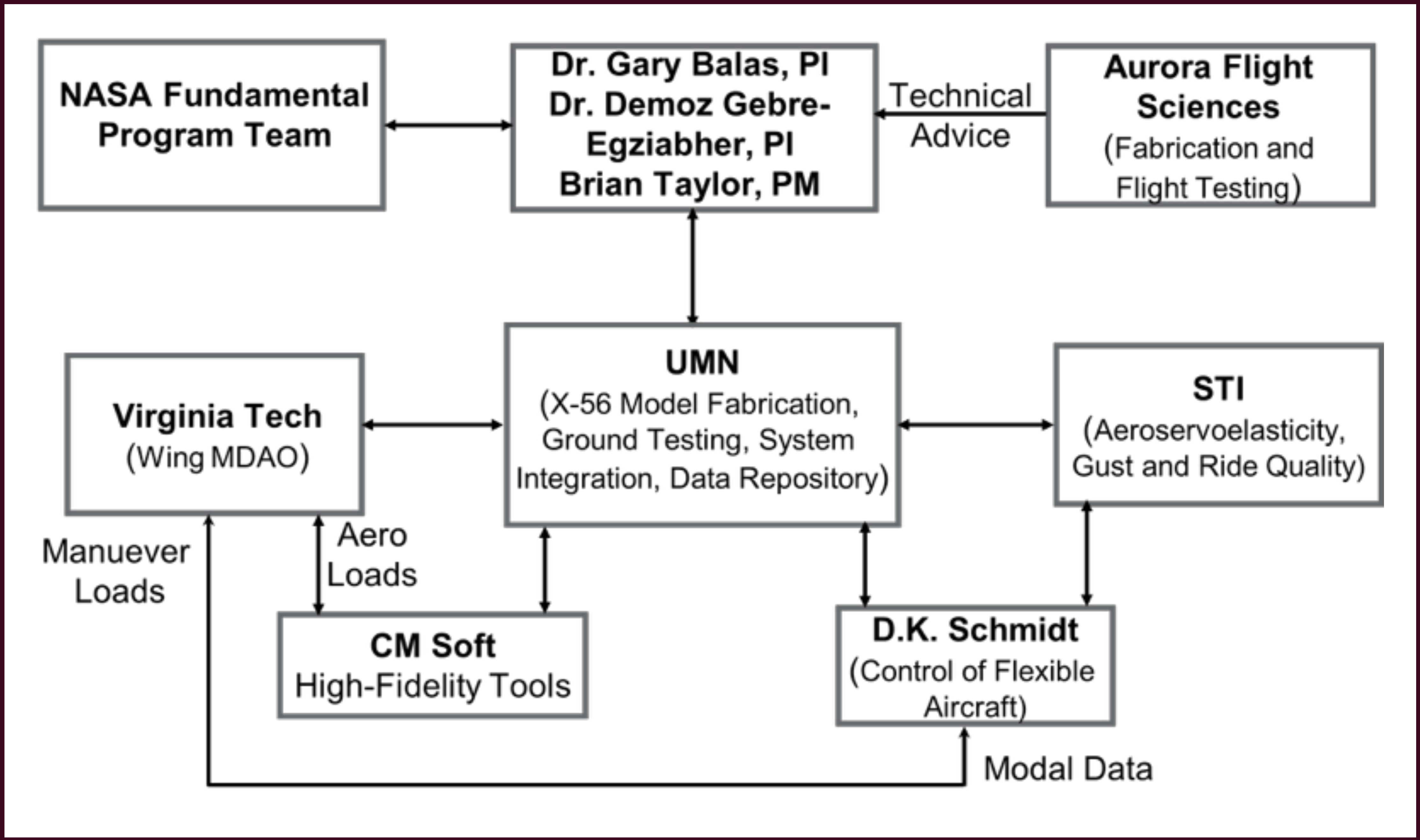
GUIDING PRINCIPLES

- Research through development, "…bring back the spirit of learning by flying" philosophy
  - Conduct flight testing early and often in the program, building on capabilities learned by previous tests
  - Validate design and analysis tools through flight test
- Everything will be open-source and published on the web
  - Resource for community to build on our success



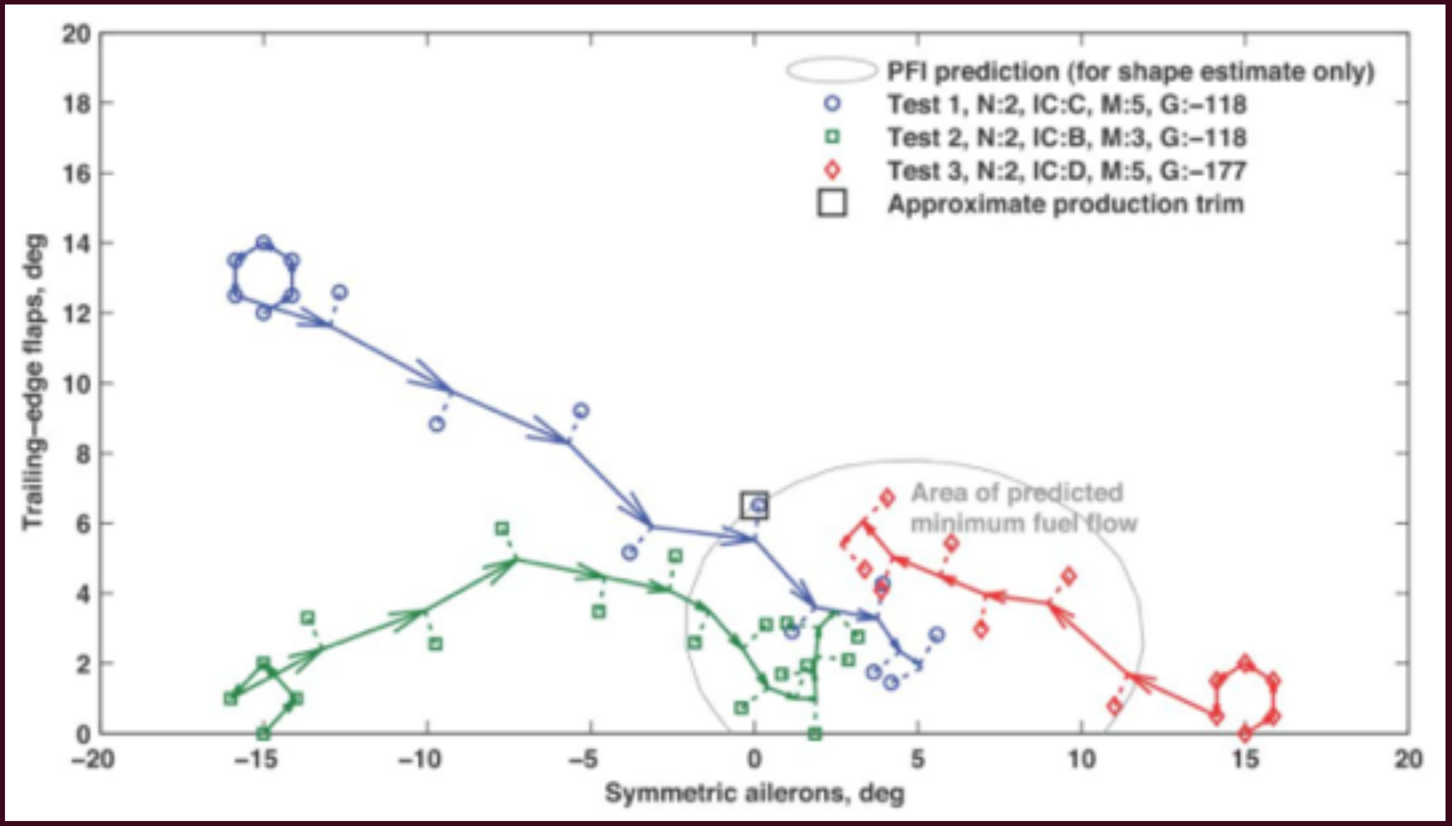
ORGANIZATION

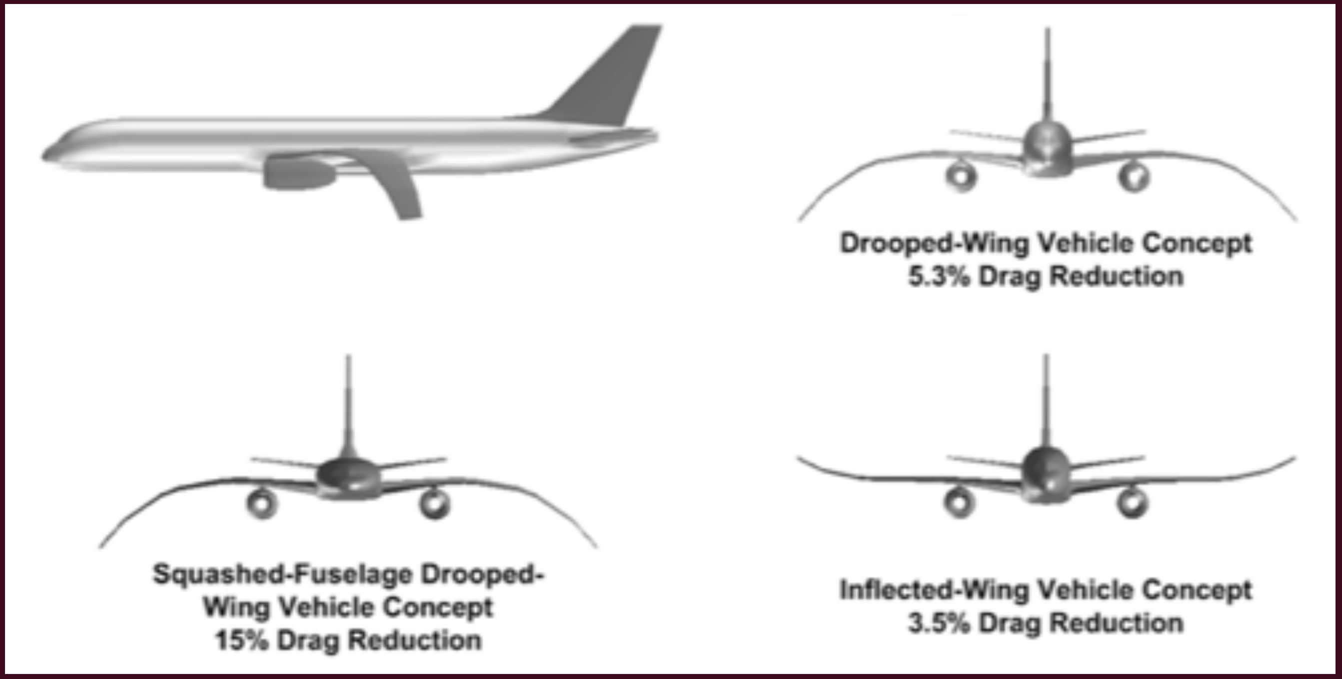
- Not a traditional University led research program



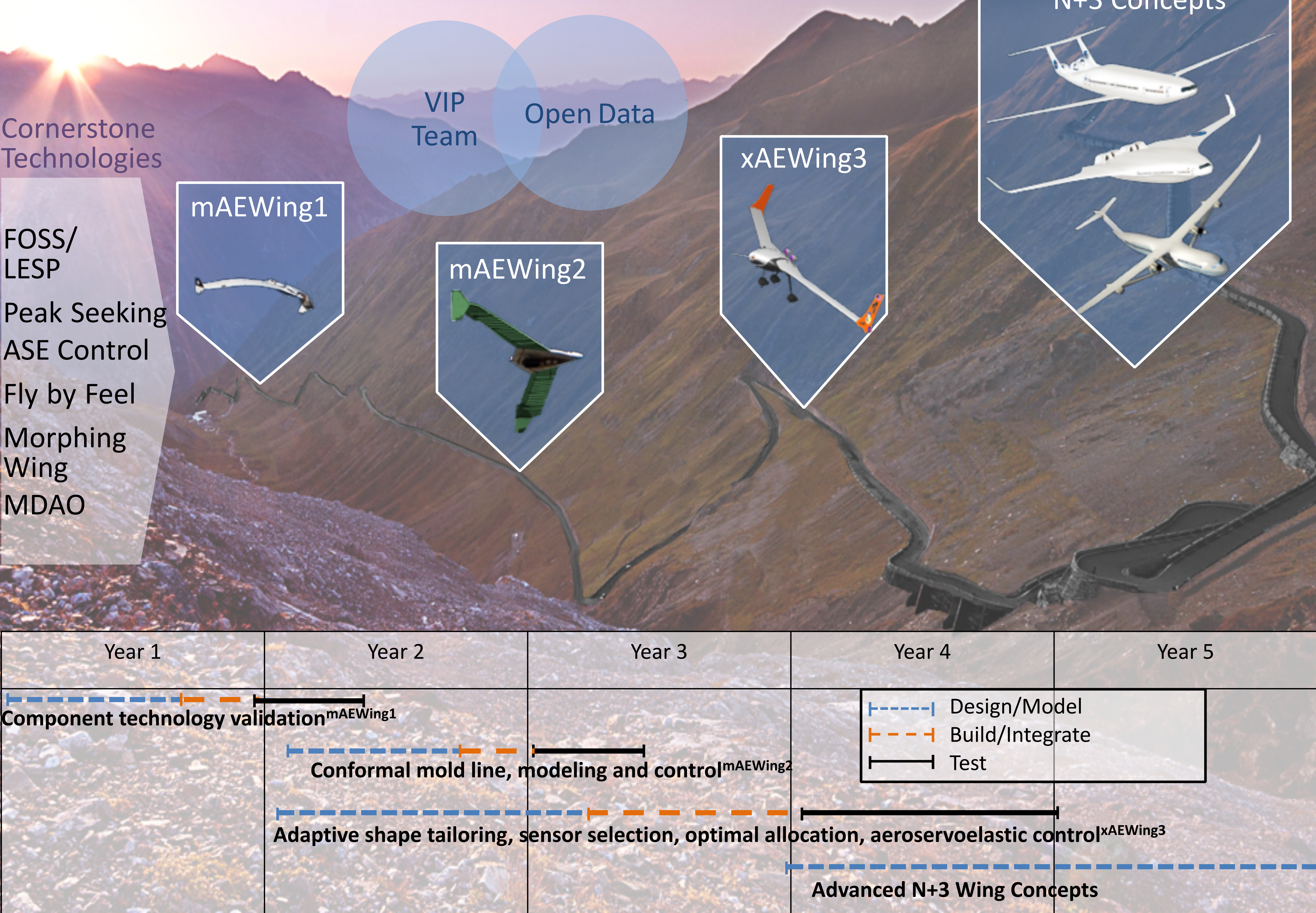
FOUNDATIONAL TECHNOLOGY

- Flutter suppression
- MDAO
- Coplanar multi-objective surfaces
- Conformal mold lines
- Optimal control allocation and load alleviation
- Shape Optimization
- Peak-seeking control laws
- FOSS
- LESP / Fly by Feel





Research through Development



mAEWing1

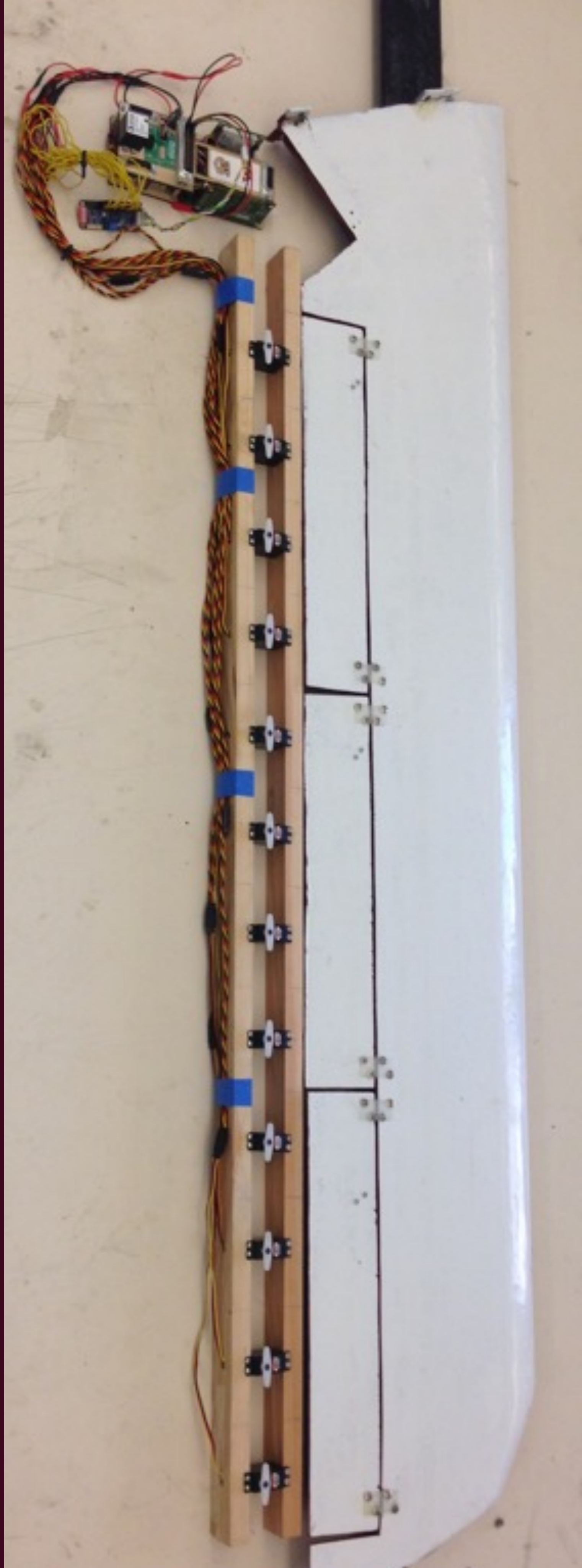
- Put foundational technologies onto a single platform
- Demonstrate that some of them can work together
- Develop and refine models and control laws

➡ Flutter suppression, open-loop shape modification, and optimal control allocation with many discrete surfaces and traditional sensors

mAEWing2

- Refine and update approaches and tools
- Begin optimizing design and more tightly integrating technologies together
- Apply and validate MDAO

➡ Same objectives as mAEWing1 with optimal sensors, effectors, and conformal mold line



xAEWing3

- Tightly integrate technologies, including FOSS, outer-loop shape control, and peak-seeking algorithms
- Demonstrate in high-fidelity environment with real-world challenges

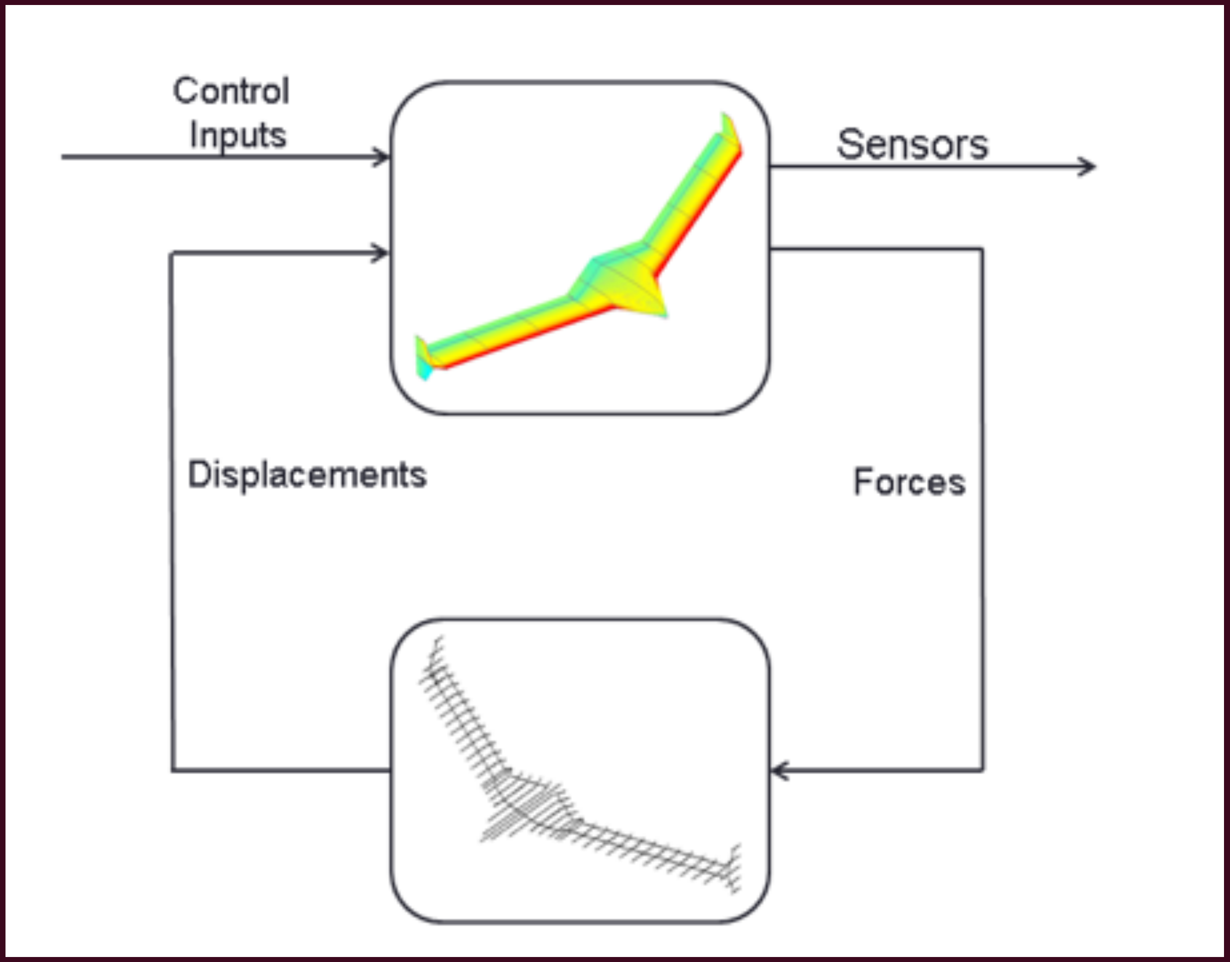
➡ Performance adaptive wing with representative structure and changing flight conditions and aircraft weight

N+3 CONCEPTS

- Extend research from subscale demonstration to commercial aircraft design
- Explore opportunities and challenges associated with full scale aircraft

TECHNOLOGICAL APPROACH

- Aeroelastic modeling
- Control law design
- Novel control effectors and sensors
- MDAO
- Curvilinear SpaRibs
- Technology maturation
- Manufacturing



AEROELASTIC MODELING

- Traditional AE modeling approach: **Linear Finite Element Models (FEMs) + Linear Parameter Varying Unsteady Aerodynamics (e.g., doublet lattice- based)**
  - Result: linear state space models suitable for analysis, simulation, and control design
- **Computational Fluid Dynamic (CFD) / Computational Structural Dynamic (CSD) Models**
  - Result: nonlinear full order models and reduced order linear parameter varying state space models (using Proper Orthogonal Decomposition (POD)).
- **Flight Dynamics Approach** - a direct extension of the framework traditionally used in the flight-dynamics community
  - Result: nonlinear rigid body dynamic + linear aeroelastic dynamic models
- All modeling approaches ***must*** consider highly coupled rigid body and structural dynamics

CONTROL LAW DESIGN

- Goals: control laws will enable reduced structural mass, reduced vehicle drag, and enhanced performance across the flight envelope
- Low Bandwidth (outer loop):
  - Aeroelastic optimal shape control (drag reduction, performance enhancement)
- High bandwidth (inner loop):
  - Primary flight control: rigid body stability augmentation and guidance
  - Flutter suppression
  - Gust Load Alleviation (GLA)
  - Control law design tightly integrating rigid-body and aeroelastic dynamics
- MDAO will incorporate control design aspects

CONTROL LAW DESIGN

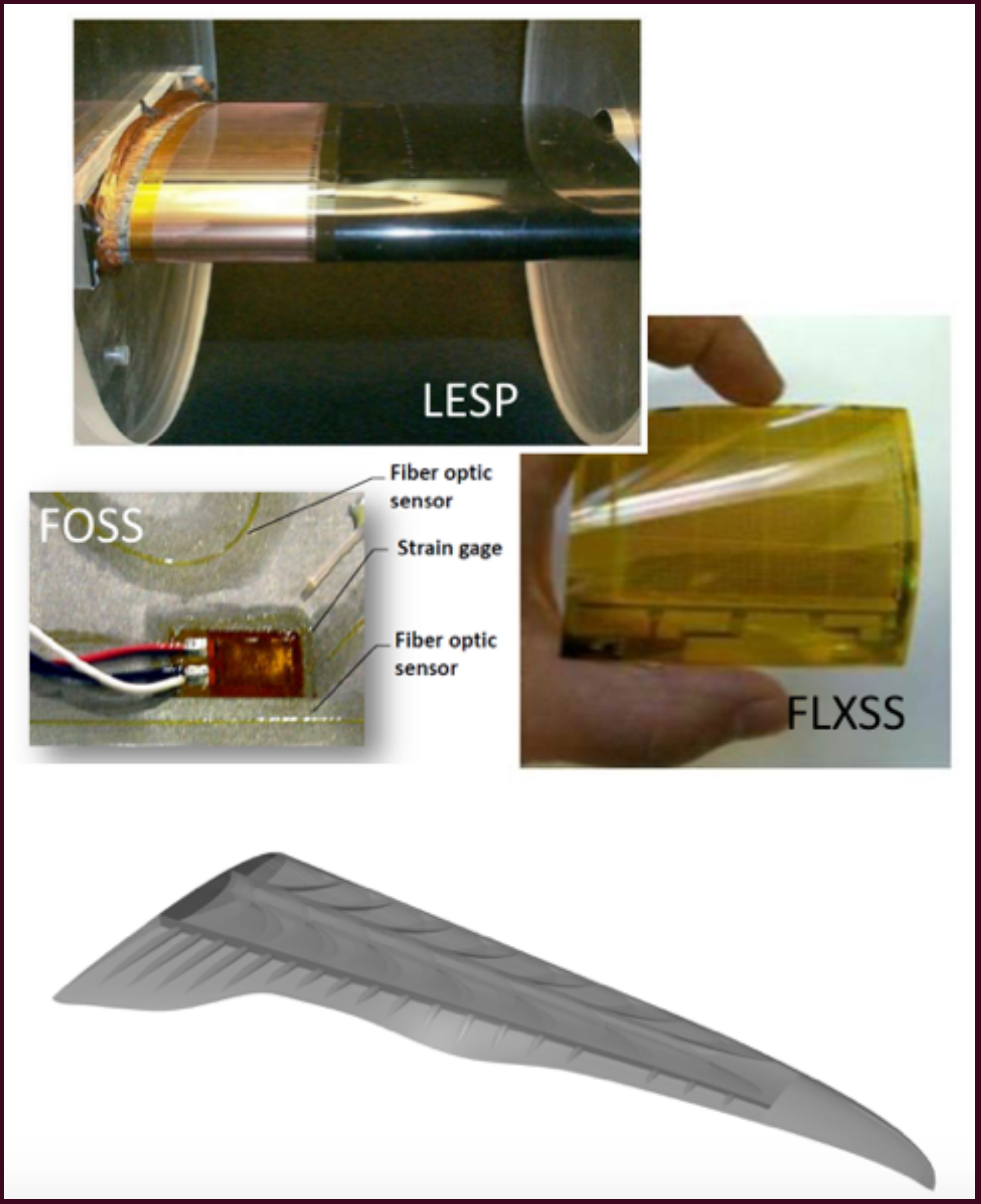
- Optimal Shape Control
  - Leverage large number of distributed control effectors and sensors
  - The optimal shape of the wing can be projected onto a small number of basis functions which sets the reference command for the shape control.
  - Peak-seeking control will be applied to find the optimal wing shape in real-time using sensor feedback
  - Recent work at NASA ARC and AFRC will be leveraged
- Flutter Suppression and GLA
  - N+3 aircraft will be lightweight with high aspect ratio leading to unavoidable adverse ASE interactions, requiring active flutter suppression and GLA
  - LPV framework will be exploited
  - Candidate control approaches: Modal Isolation and Damping for Adaptive Aeroservoelastic Suppression (MIDAAS), Linear Parameter Varying synthesis (LPV), Identically Located Actuator and Force (ILAF) structural mode control, μ-synthesis
- In order to enable integrated active ASE control to become a reality, an advanced tool chain for modeling, analysis, controller synthesis, and novel robust stability and performance analysis will be developed.

NOVEL CONTROL EFFECTORS AND SENSORS

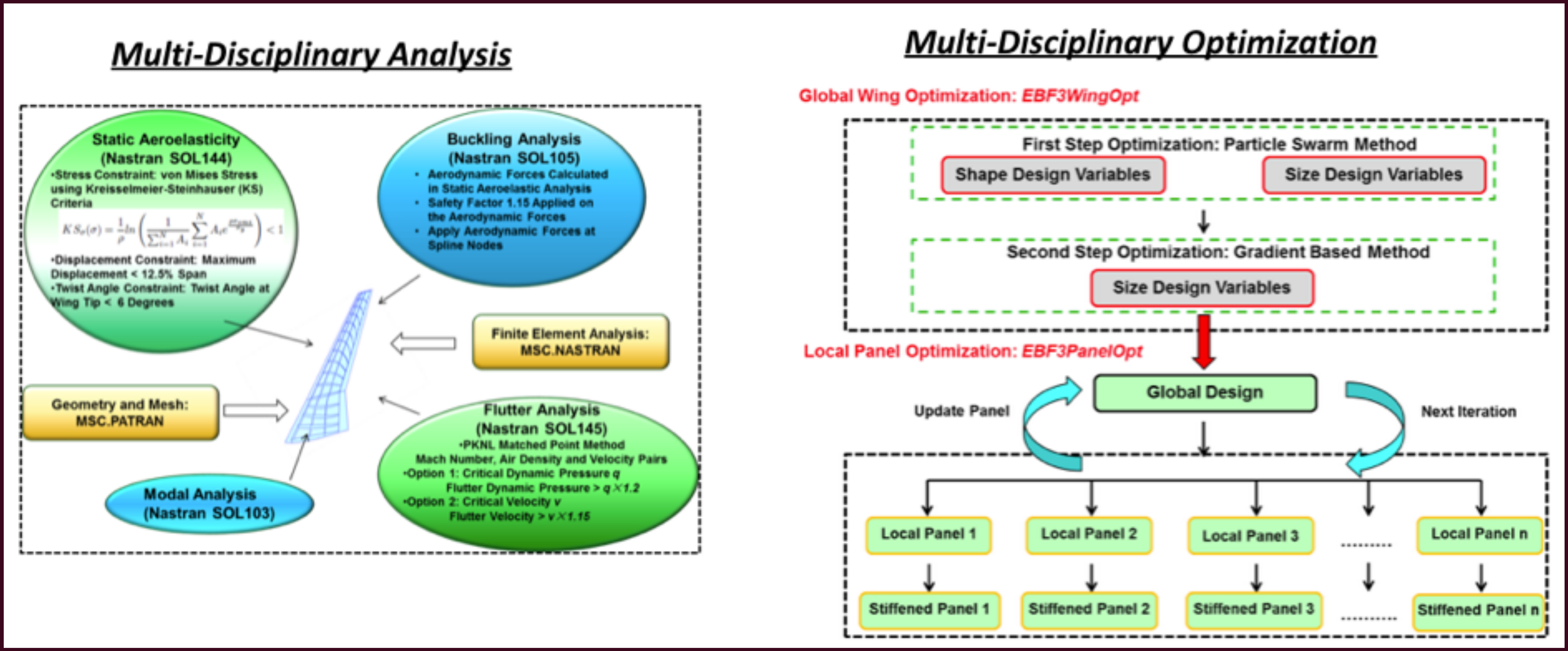
- Appropriate selection of control effectors and sensors is critical to the success of PAAW
  - Must meet multiple control demands: primary flight control, flutter suppression, load alleviation, and wing shape control
  - Innovative sensors will enhance the ability to rapidly estimate the vehicle state, including estimation of the aeroelastic shape
  - Innovative effectors will enable rapid control of the vehicle state, including commanding the aeroelastic shape

NOVEL CONTROL EFFECTORS AND SENSORS

- Innovative sensor technology
  - Leading Edge Stagnation Point (LESP)
  - Fiber Optic Strain Sensing (FOSS)
  - FLexible multipleXed Strain Sensor (FLXSS)
- Envisioned control effector technology and strategy
  - Distributed control effector network (many effectors to accompany many sensors)
  - Optimal and adaptive control allocation
  - Conformal gap-free surfaces via elastic membranes



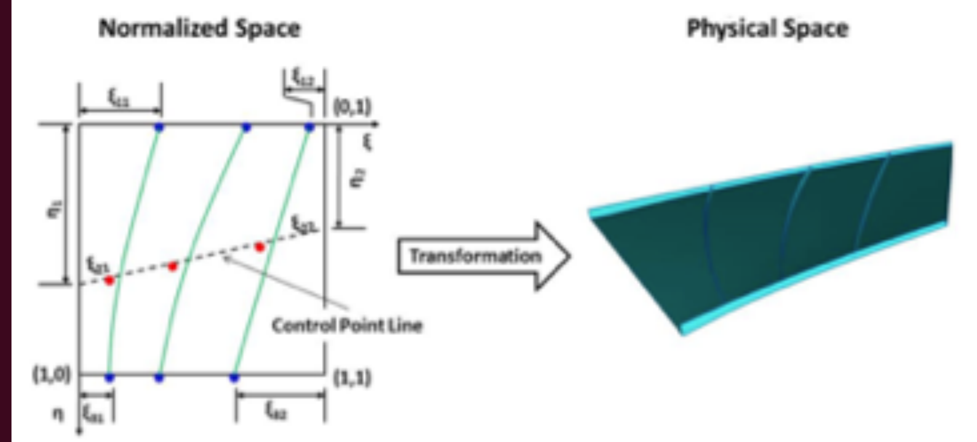
MDAO-*EBF3GLWingOPT*



- Multi-disciplinary analysis
  - Automatic parameterization and mesh generation of aircraft wing
  - Integration of modal analysis, static aeroelastic analysis, flutter analysis and buckling analysis
- Multi-disciplinary optimization
  - <u>Global Wing Optimization:</u> topology and sizing optimization for the wing skins, spars, and ribs
  - <u>Local Panel Optimization:</u> BCs from global wing discplacement results enforced to panel edges; sizing optimization implemented for each panel subject to local stress and buckling constraints

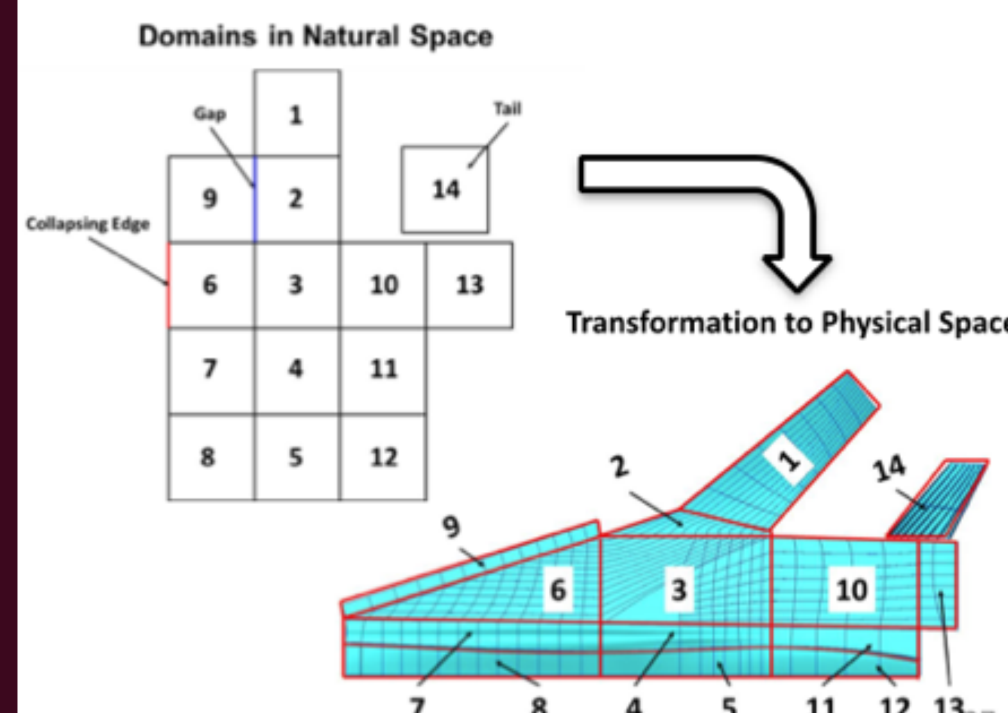
CURVILINEAR SPARIBS

- SpaRibs: curvilinear spars and ribs
- Linked shape method: define a set of spars or ribs in one wing section
- Normal space and physical space
  - Curvilinear SpaRibs geometry defined with third order B-splines in the normal space
  - Define B-splines using the start, control and end points placed in normal space (η,ξ)
  - Transform the curves from the normal space into the physical space
- Six parameters needed to define one set of SpaRibs
- C^0 continuity condition is enforced



Parameter	Description
P_1	***Number of SpaRibs***
P_2	η_1
P_3	***η_2***
P_4	ξ_{11}/ξ_{12}
P_5	***ξ_{21}/ξ_{22}***
P_6	ξ_{31}/ξ_{32}

Application of the Parameterization(Boeing HSCT)

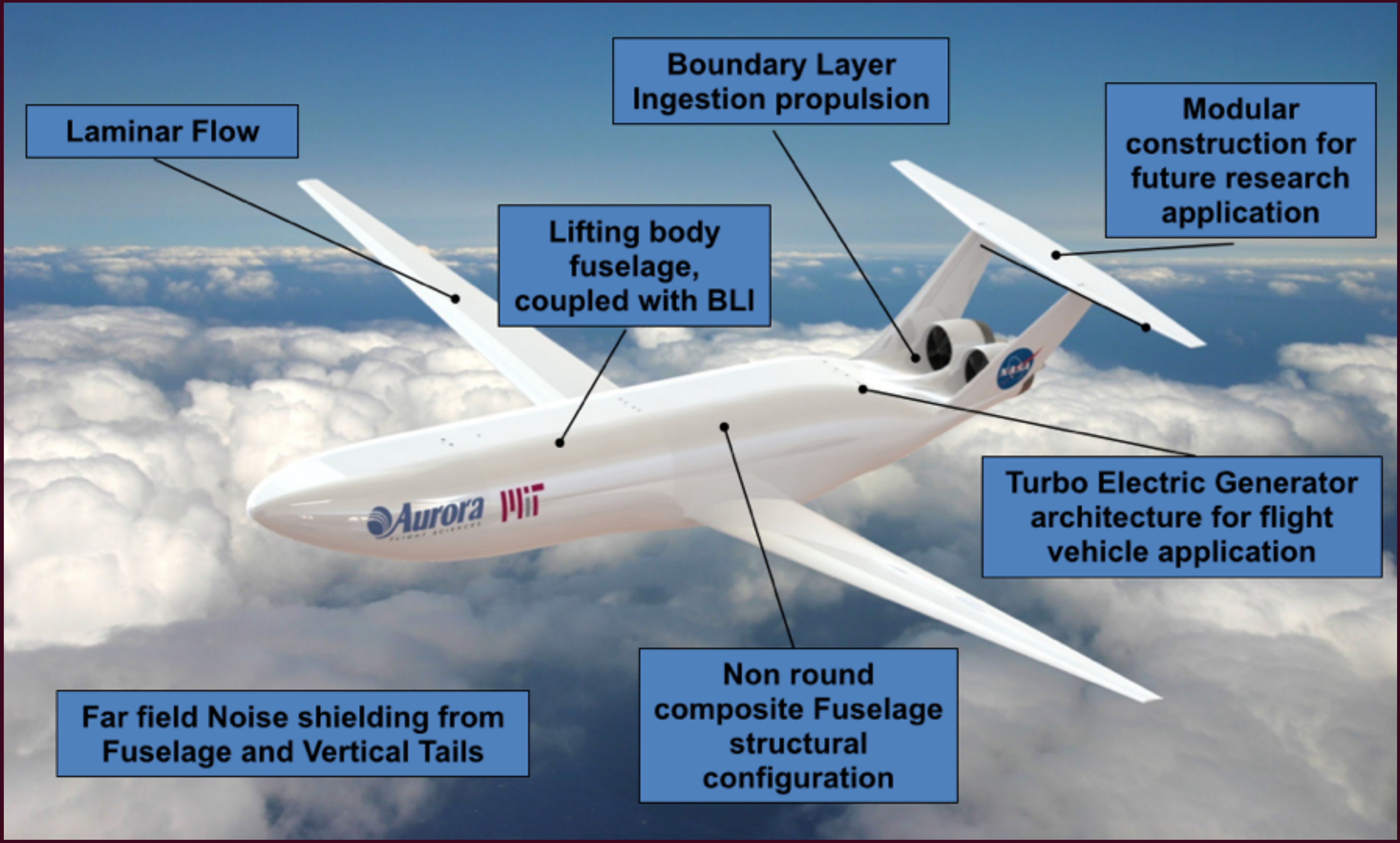


NASA N+3 PROGRAM

- Lead by University partner (MIT)
- Aurora supported with engineering skills in specific specialties (propulsion, systems, structures) in initial phase.
- Aurora lead manufacturing, logistics, test coordination, and model safety verification in Phase 2 (Testing in NASA Langley 14′x22′ wind tunnel.)

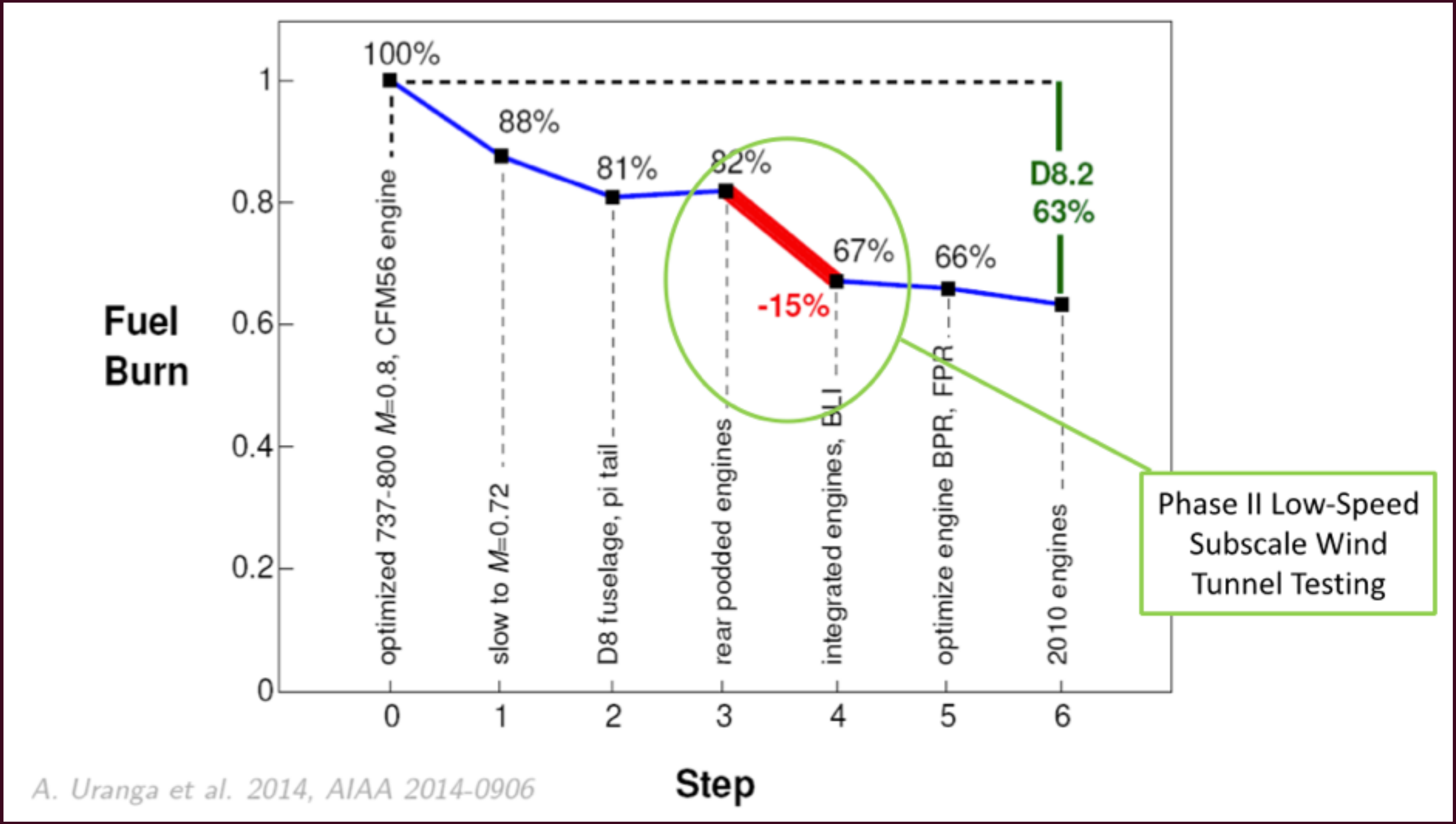
D8 AIRCRAFT CONCEPT ENABLING TECHNOLOGIES

- Technologies identified through N+3 and other Fundamental Aeronautics research



N+3 STEP-BY-STEP FUEL BURN REDUCTION

- Results from phase 1 lead thinking and effort for Phase 2

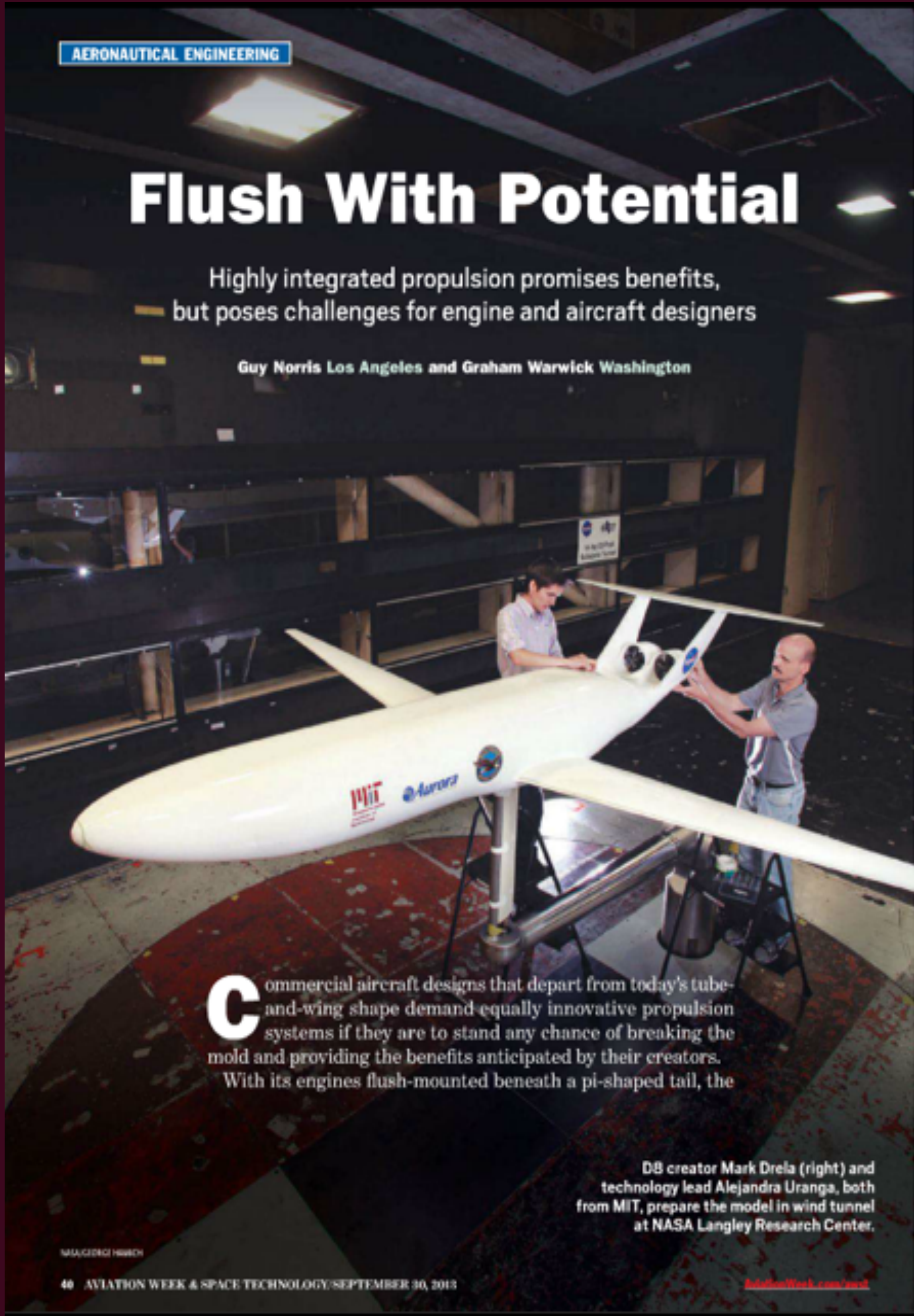


N+3 TECHNOLOGY DEVELOPMENT

- Cutting edge R&D in civilian transport configuration for NASA Aeronautics
- Achieves NASA's N+3 performance goals:
  - 60% reduced fuel consumption
  - 80% NOX reduction
  - -71 dB noise reduction
- First principles based configuration modeling
- MIT led N+3 Phase I and II program with Aurora and Pratt & Whitney
- Wind tunnel testing using 3D printed models currently underway
  - Initial testing validated performance estimates

Massachusetts Institute of Technology

Pratt & Whitney
A United Technologies Company


AERONAUTICAL ENGINEERING

Flush With Potential

Highly integrated propulsion promises benefits, but poses challenges for engine and aircraft designers

Guy Norris Los Angeles and Graham Warwick Washington

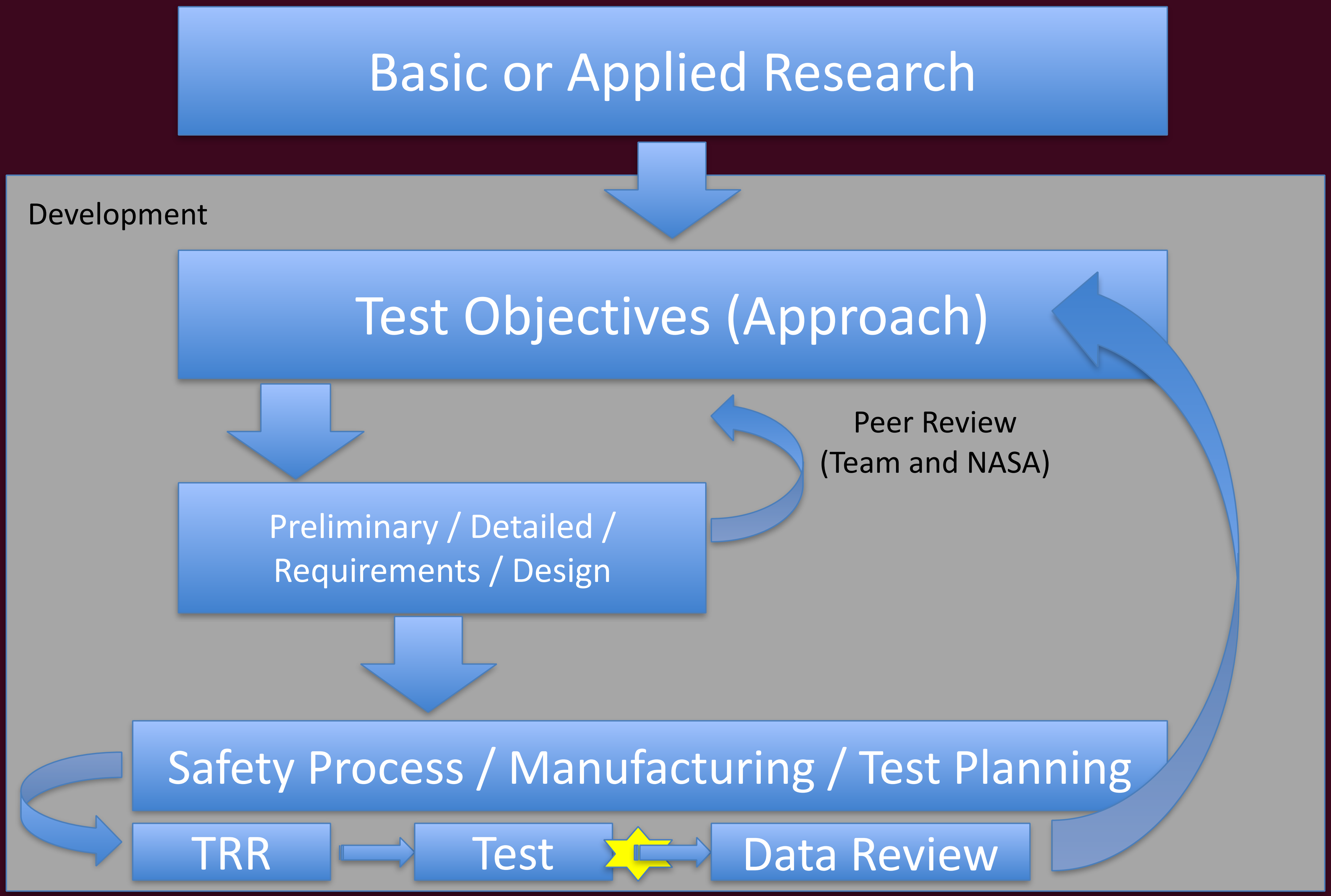
Commercial aircraft designs that depart from today's tube-and-wing shape demand equally innovative propulsion systems if they are to stand any chance of breaking the mold and providing the benefits anticipated by their creators.

With its engines flush-mounted beneath a pi-shaped tail, the

D8 creator Mark Drela (right) and technology lead Alejandra Uranga, both from MIT, prepare the model in wind tunnel at NASA Langley Research Center.

40 AVIATION WEEK & SPACE TECHNOLOGY/SEPTEMBER 30, 2013

FROM RESEARCH TO FLIGHT (DEVELOPMENT)



DEVELOPMENT

- This program calls for a high amount of flight test vehicles with modifications and or new construction
- This requires navigating through the design / build / flight test cycle quickly and efficiently
- This is helped through enabling new technologies (such as 3D printing) and through starting from known vehicles
- Navigating the safety process with new technologies can add significant overhead and oversight unless managed properly, as was done on N+3 with 3D printed structures used in the NASA wind tunnel

FROM RESEARCH TO FLIGHT (DEVELOPMENT)

- The X-56A Multi-utility Aeroelastic Demonstration (MAD) is an innovative modular unmanned air vehicle designed to test active flutter suppression and gust load alleviation. The X-56A demonstrator will test to the edge of the flight envelope where flutter, the potentially catastrophic dynamic coupling that can occur between the elastic motion of the wing and the aerodynamic loads acting on it, occurs.

Parameter	BFF	Mini MUTT
Mass (kg)	*5.439*	*6.384*
C.G from Nose	*.5907*	*.5916*
*Ixx (kg*m^2)*	*2.5*	*2.6*
*Iyy (kg*m^2)*	*.36*	*.32*
*Izz (kg*m^2)*	*2.38*	*2.82*
*Ixz (kg*m^2)*	*0*	*0*

FACILITIES

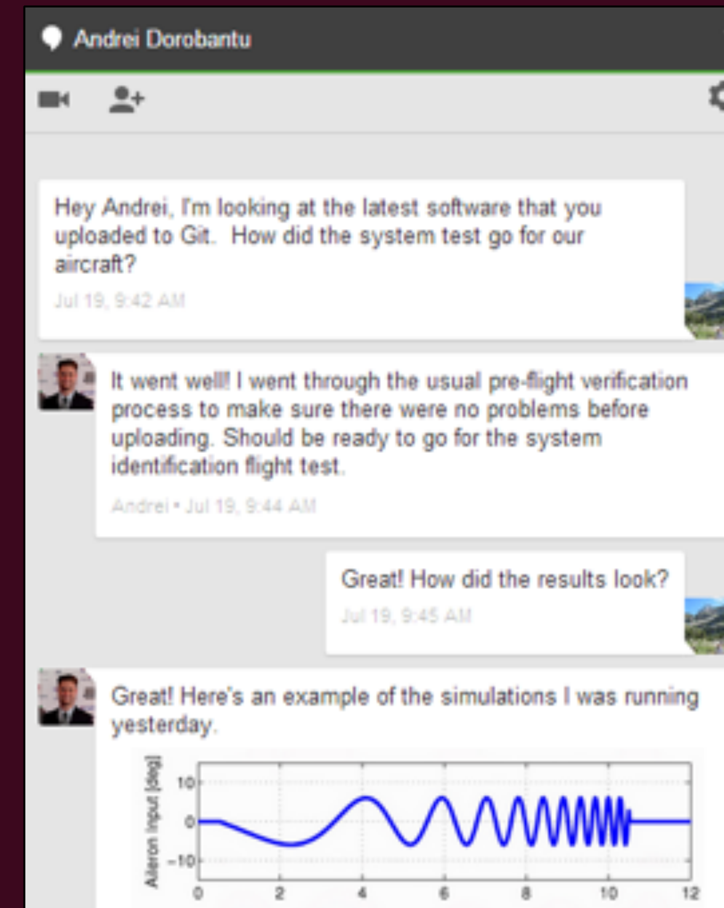
- VT 6′ by 6′ wind tunnel, structures and materials lab, and high performance computational resources for MDAO
- Ground vibration test facility and wind tunnels at UMN
- UAV Laboratories, aircraft infrastructure, and mini MUTT aircraft at UMN
- Aurora composite manufacturing and integration of complex aircraft wings

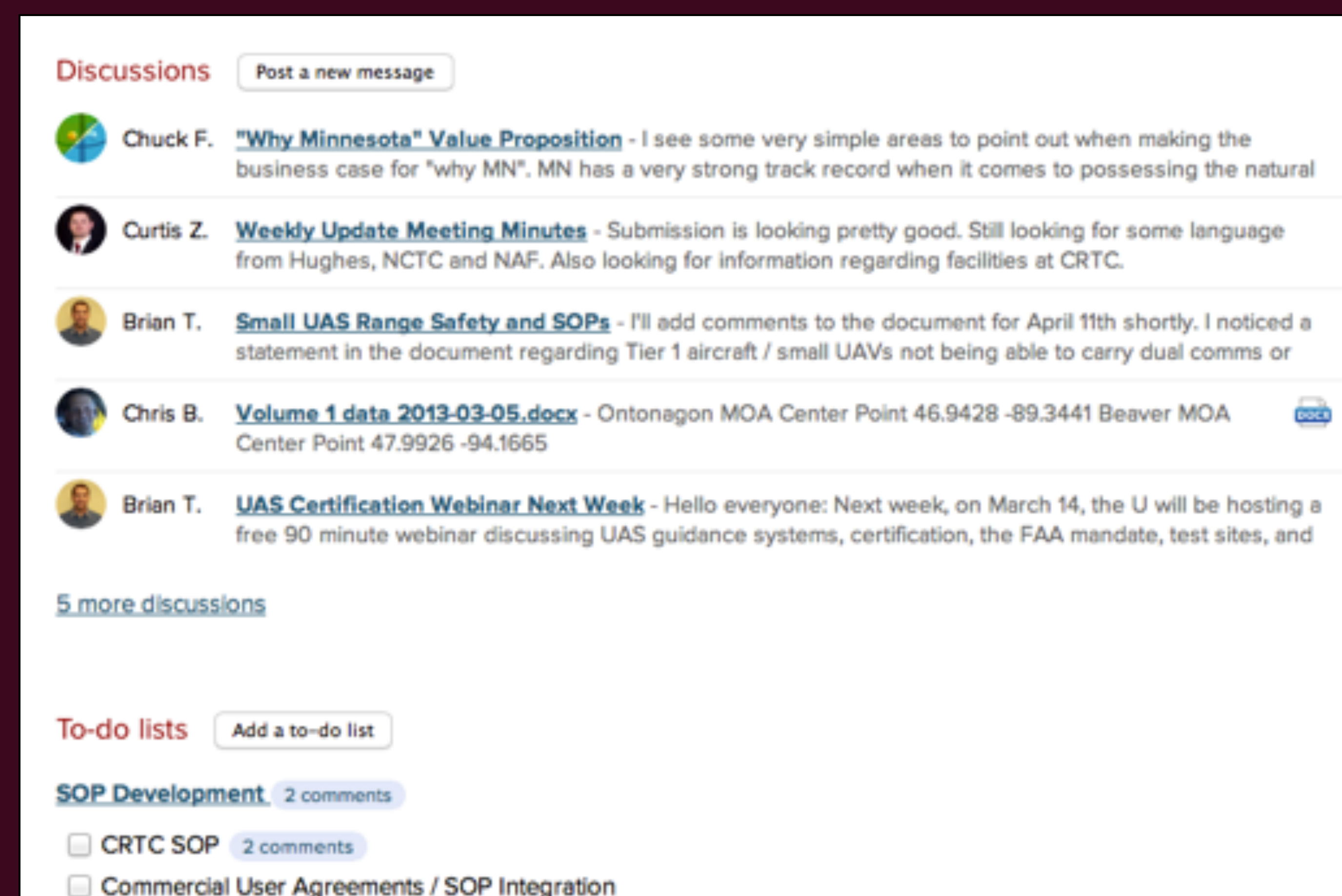
WHY US

- University of Minnesota
  - Systems integration, control law design, model reduction
- Systems Technology Inc.
  - Modeling, simulation, control law design
- Virginia Polytechnic Institute and State University
  - MDAO, curvilinear SpaRibs
- Aurora Flight Sciences
  - Fabrication and integration of complex wings
- CM Soft Inc.
  - Aerodynamic modeling
- Schmidt and Associates
  - Modeling and control law design

MANAGEMENT PLAN

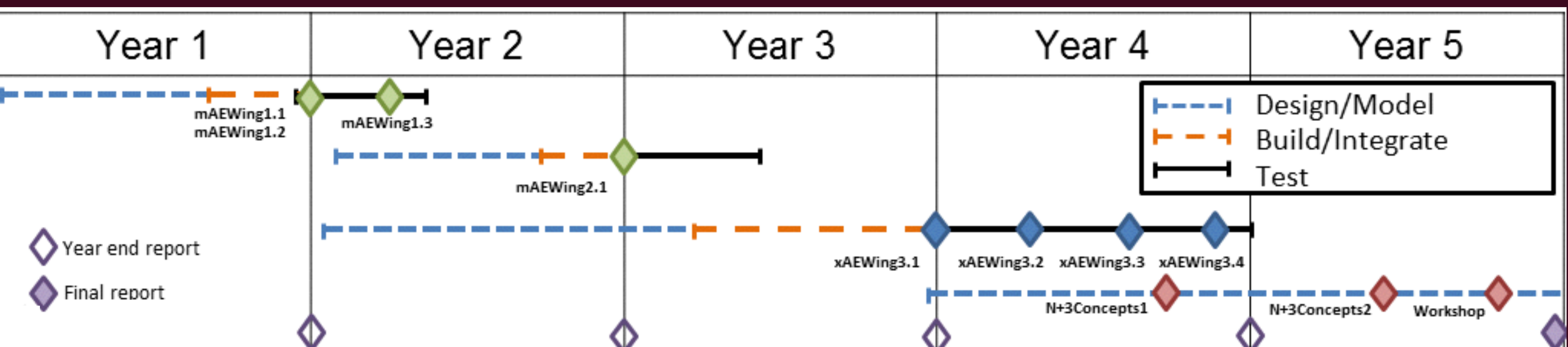
- Virtual Integrated Product (VIP) Teams
  - Cohesive integrated team made up of people from multiple disciplines located around the country
  - No throwing work over the fence
  - Many software tools to help
- Open collaboration with NASA Researchers
  - Quarterly strategic meetings
  - Monthly tactical meetings
  - Twice weekly standup status meetings





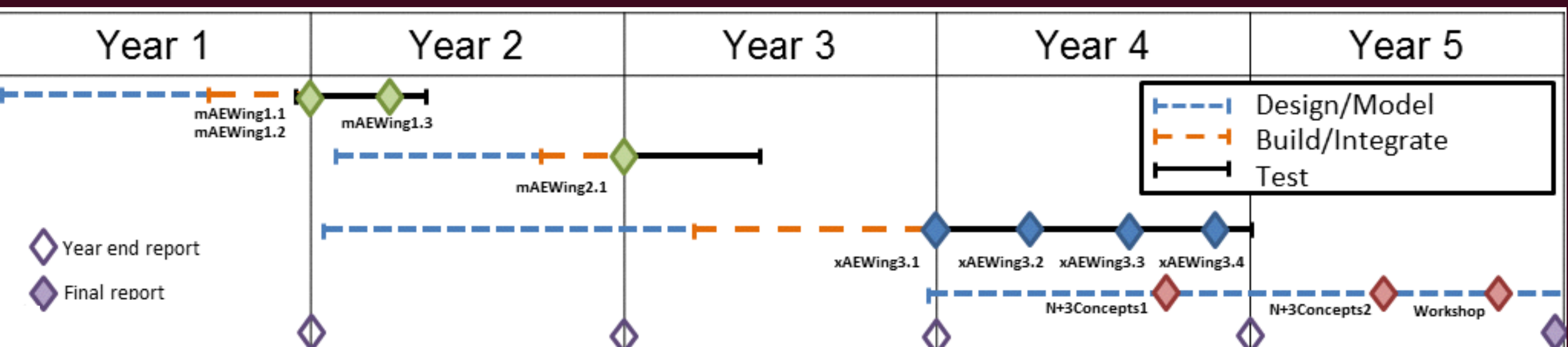
SCHEDULE AND MILESTONES

- Year 1 and 2: develop and validate technologies and design tools on mini MUTT aircraft
- Year 3 and 4: integrate technologies into X-56 and validate design tools for a structurally similar aircraft
- Year 5: extend design to an N+3 aircraft



SCHEDULE AND MILESTONES

- mAEWing1.1: flutter suppression using dedicated surfaces and traditional sensors
- mAEWing1.2: open-loop shape modification
- mAEWing1.3: flutter suppression and shape modification using multi-objective effectors
- mAEWing2.1: re-design with MDAO, optimal sensor placement and conformal mold line effectors

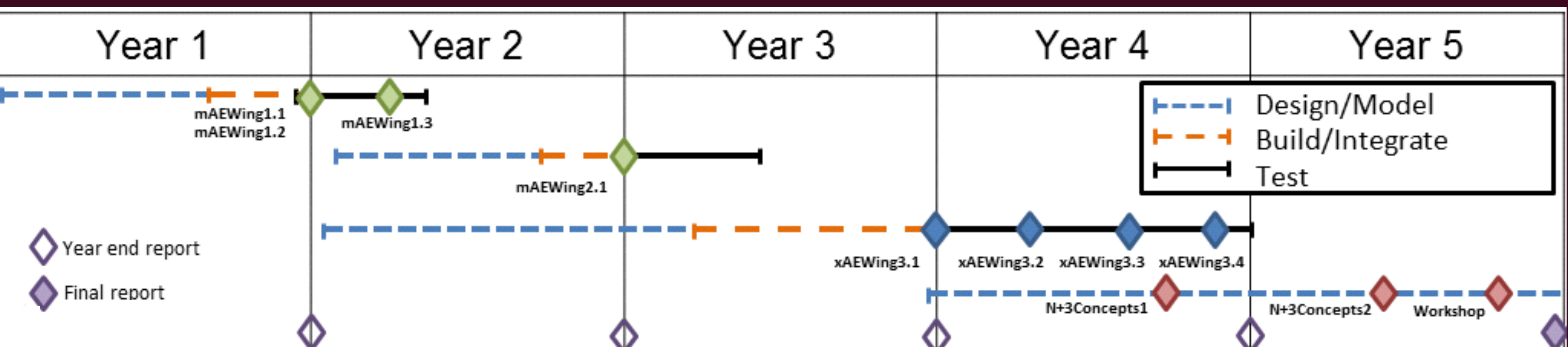


SCHEDULE AND MILESTONES

- xAEWing3.1: flutter suppression, open-loop shape modification, multi-objective effectors, and conformal mold line on X-56A
- xAEWing3.2: validate shape feedback sensors on the ground
- xAEWing3.3: demonstrate the addition of closed-loop shape control, gust load alleviation, and peak-seeking control laws in flight by showing performance adaptation for cruise, takeoff, and landing flight conditions
- xAEWing3.4: demonstrate performance adaptation in the presence of changing vehicle weight

SCHEDULE AND MILESTONES

- N+3 Concepts1: investigate addition of distributed propulsion in MDAO, investigate use of smart materials for adaptive aeroelastic tailoring and control effectors to improve performance
- N+3 Concepts2: design a notional full-scale N+3 performance adaptive wing
- N+3 Workshop: host a workshop on tools and design techniques for performance adaptive wings



SUMMARY

- Developing performance adaptive wing for N+3 aircraft
  - Lightweight, aerodynamic airframe
  - Adapts in real-time to current flight condition to maximize performance
- Build up approach of many ground and flight tests
  - Validate components prior to system level integration and validation on X-56A aircraft
- Results applicable to full scale commercial aircraft
- Publish all tools, data, results and analysis open-source and online as a resource to the community (paaw.net?)


Name
- trunk
  - Propeller Data
  - Software
  - Documentation
  - FlightData
    - System_Development
    - Control_Laws
      - thor_flight90_group3_outerloop_2013_05_08.mat
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      - thor_flight88_group2_outerloop_2013_05_08.mat
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AREAS FOR COLLABORATION

- Model development
- MDAO
- Novel sensors (FOSS / LESP)
- Peak-seeking control laws
- Optimal control allocation
- Conformal mold line materials

- Data and models